Dual-purpose Heat Transfer Fluids for Concentrated Solar Power

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CSP Program Review

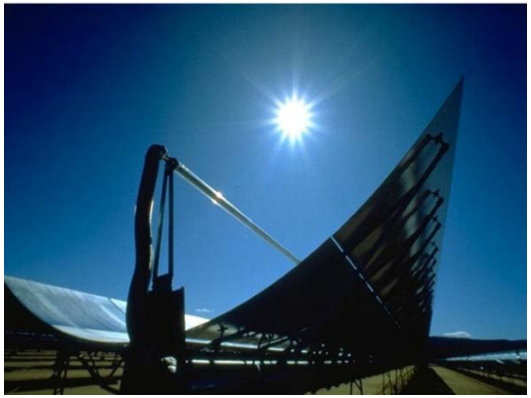
Project Start Date: March 5, 2010

Project Rationale

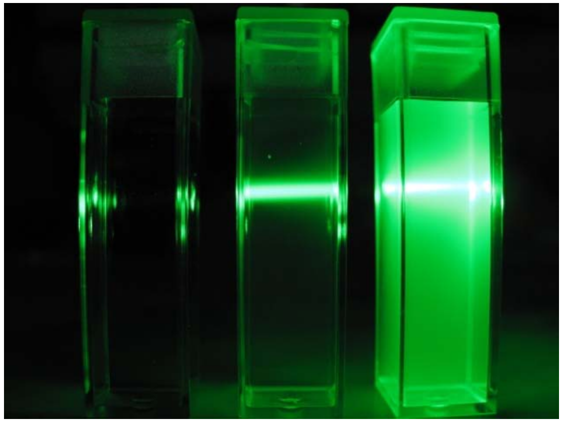
"….to make Concentrated Solar Power (CSP) cost competitive in the intermediate power markets by 2015 (~$0.07/kWh with 6 h storage) and in baseload power markets ($0.05/kWh with 16 h storage) by 2020…." Source: DOE –SETP website

Potential technology areas identified for CSP to realize cost reductions

- Receiver technology
- Concentrator design
- Advanced High Temperature Fluids (HTFs) with enhanced thermal properties
- Thermal energy storage
- Plant size



Solar trough

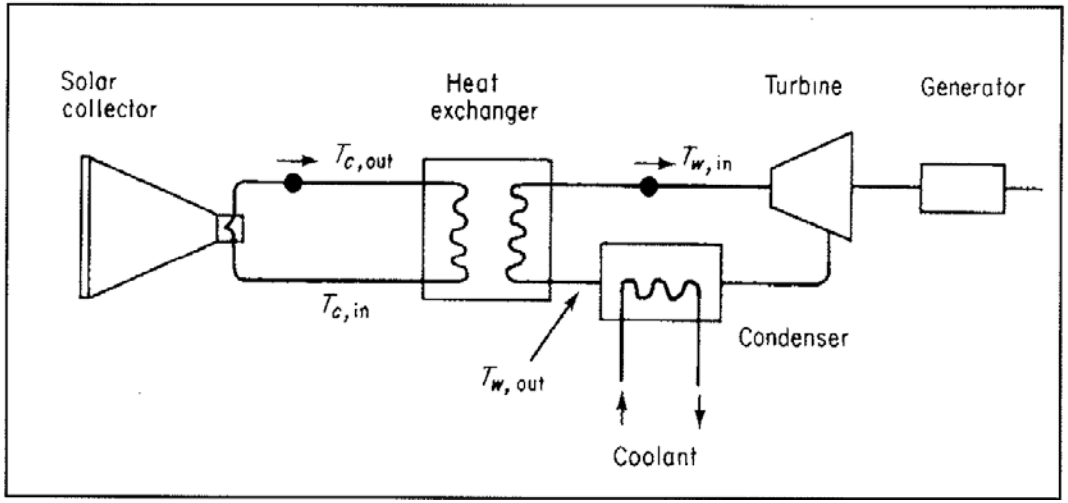


Silica/Therminol nanofluid

Project Objective

- ***The goal of the project is to develop advanced HTFs by incorporating multifunctional engineered nanoparticles. The advanced HTF as a single medium will play the role of a enhanced heat transfer fluid and as a thermal storage system.***
  - ✓ Use simulations/modeling to identify candidate materials systems that will provide enhanced thermal properties to HTFs and thermal storage
  - ✓ Develop processing routes to fabricate the appropriate nanoparticles of the selected material system(s) and particle design, and incorporate them in commercial HTFs
  - ✓ Validate the improved behavior of the advanced HTFs by extensive laboratory scale testing
  - ✓ Simulation of heat transfer enhancement and overall improved performance
  - ✓ Demonstrate the performance of the advanced HTFs on a test bed in collaboration with a commercial partner/national lab
  - ✓ Transfer technology to a commercial partner

Background



Schematic of Various Components of Solar to Electric Energy Generation

- Overall efficiency of solar Rankine cycle depends on $T_{w,in}$
- A higher $T_{c,out}$ will result in higher $T_{w,in}$; hence higher system efficiency
- Minimizing the temperature drop from pipe wall to HTF on the collector side will enhance $T_{c,out}$
- Higher $T_{c,out}$ can be achieved with a HTF with increased density, improved thermal properties (conductivity, heat transfer, specific heat)

Storage of thermal energy in HTF will provide added advantage

Nanofluids

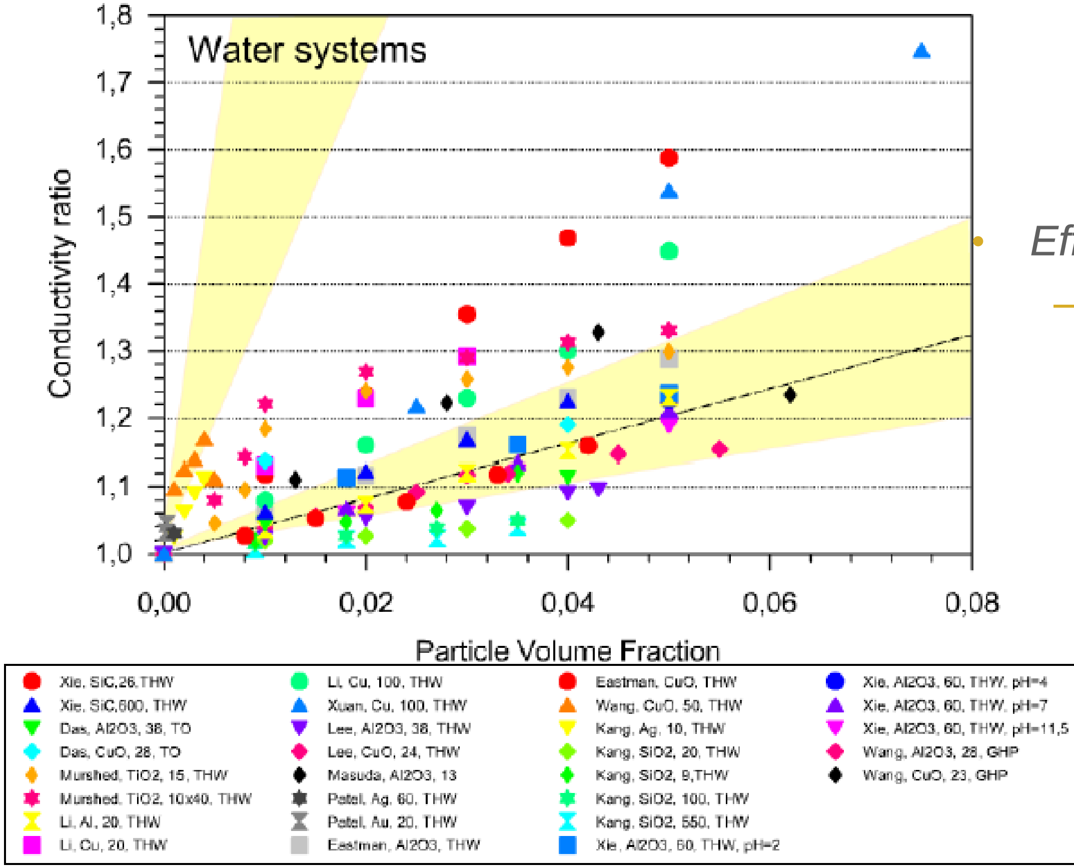


Fig. 5) Comparison of results for water based nanofluids with the two groups from organic nanofluids. The dotted line gives a theoretical result from sect. 4

HEAT TRANSFER MECHANISMS IN NANOFLUIDS -- EXPERIMENTS AND THEORY --

S Kabelac, J F Kuhnke

Nanofluids: fluid in which nanometer-sized particles are uniformly suspended

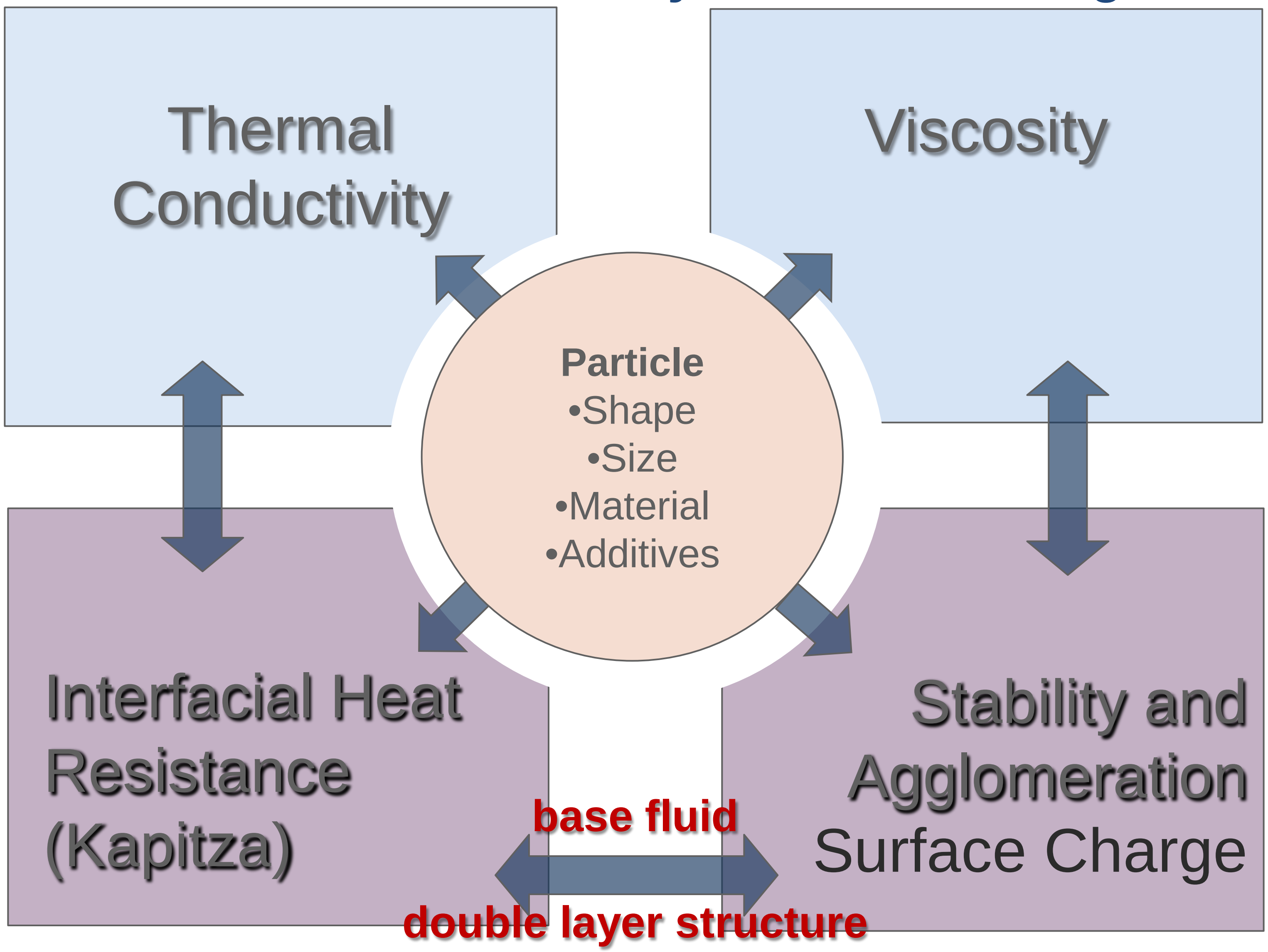
- *Effective Medium Theory*
  - Spherical particles of high thermal conductivity k_1 suspended in fluid of low thermal conductivity k_0, with volume fraction $\varphi << 1$

$$k_{eff}/k_0 = 1 + \frac{3(k_1 - k_0)}{k_0 + k_1}\varphi \approx 1 + 3\varphi$$

conductivity does NOT depend on:

- particle material ($k_1 >> k_0$)
- particle size
- temperature

Nanofluids are multivariable systems - Challenges



Efficiency of Nanofluids

$$h = \frac{\Delta Q}{A \Delta T}$$

where

- h = heat transfer coefficient, W/(m^{2}K)
- ΔQ = heat input or heat lost,
- A = heat transfer surface area, m^2
- ΔT = difference in temperature between the solid surface and surrounding fluid area, K

Property Based Figures of Merit :

laminar and turbulent flow

$$\left.\begin{aligned} \frac{k_{nf}}{k_0} &= 1 + C_k \phi \\ \frac{\eta_{nf}}{\eta_0} &\approx 1 + C_\eta \phi \end{aligned}\right\} \boxed{C_\eta / C_k < 4}$$

Prasher R. et al., Appl. Phys. Lett. **89**, 133108 (2006).

$$M = \frac{\rho^{0.8} c_p^{0.3} k^{0.6}}{\eta^{0.4}} \; ; \; Mo_{nf}/Mo_0 > 1$$

W. Yu et al., *Appl. Phys. Lett., 96, 2010, 213109*

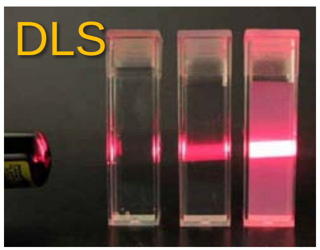
Experimental Protocol

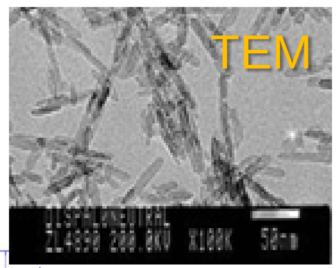
- Optimization of material properties for nanofluid development

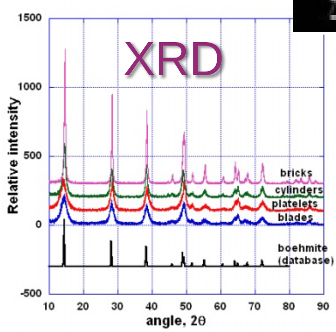
Effect of
- Particle shape
- Particle size
- Base fluid effect
- Additives

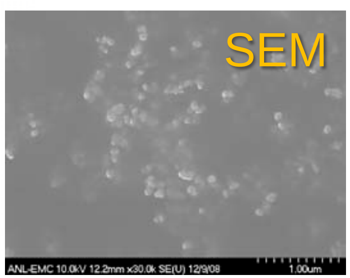
on
- Thermal Conductivity
- Viscosity

→ **Heat transfer coefficient**





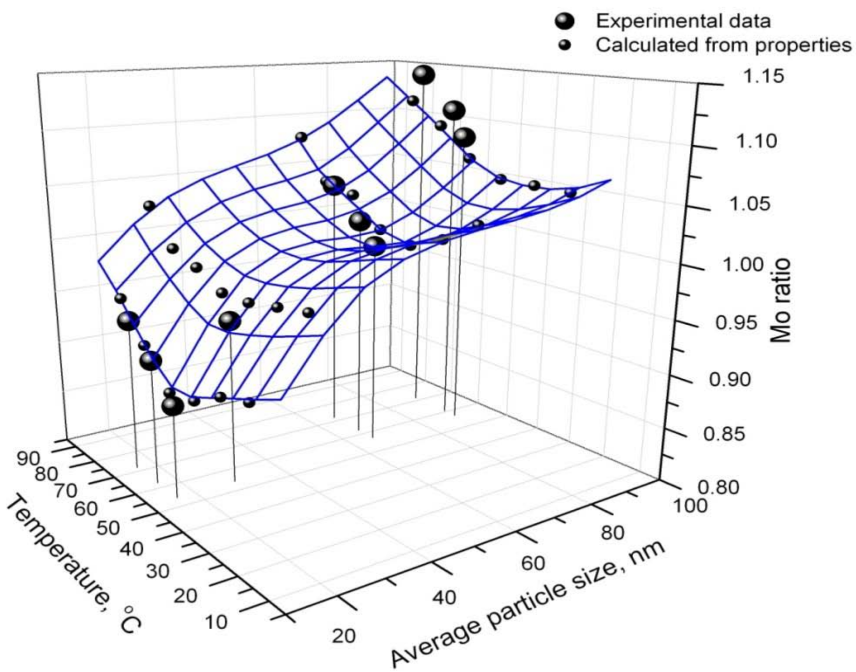


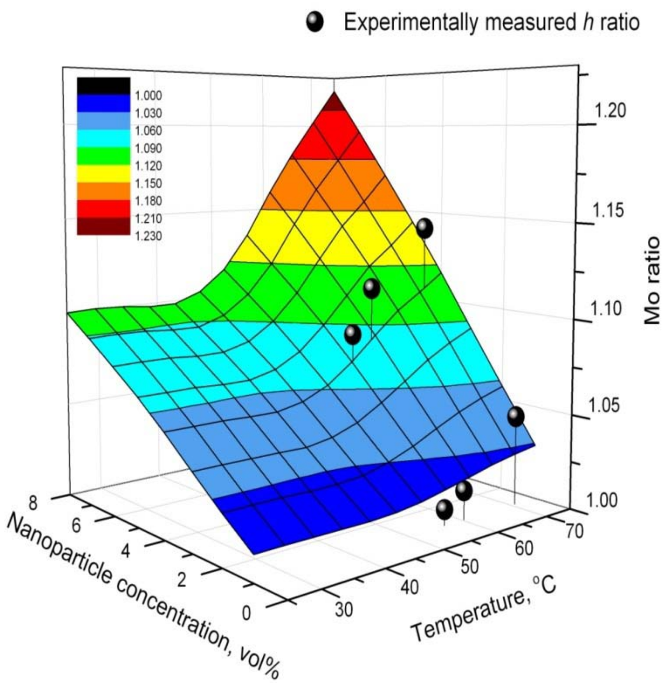


Rotational Viscometer

- Testing of nanofluid performance at various temperatures

Comparison of experimental data and estimation from the Figure of Merit (turbulent flow) for EG/H2O (50/50)





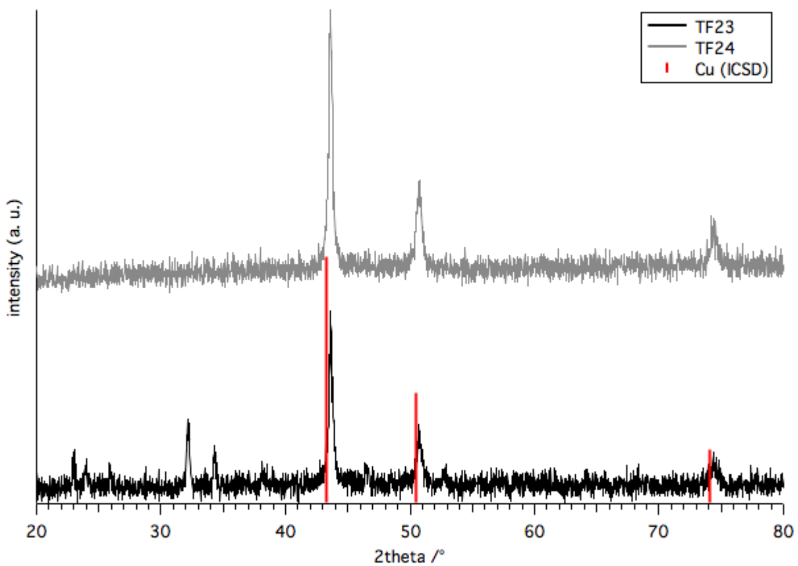
Particle Size Effect

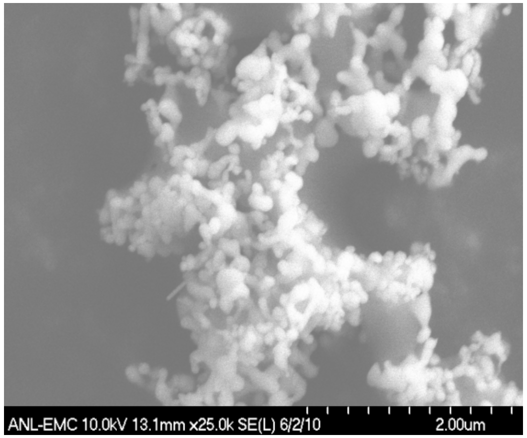
Particle Concentration Effect

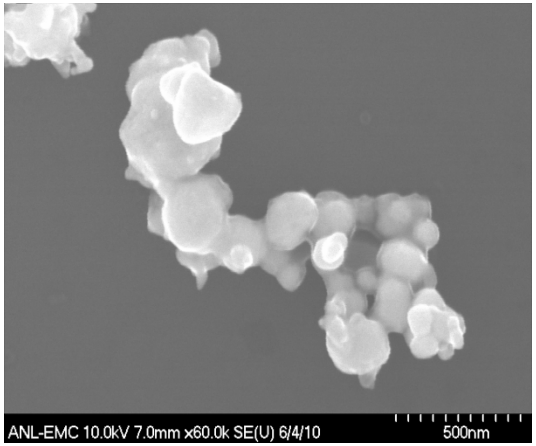
Accomplishments

Cu nanoparticles in Therminol HTF

- Chemical process
- Phase pure Cu nanoparticles synthesized
- Nanoparticles size ~ 150-200 nm (dynamic laser scattering)



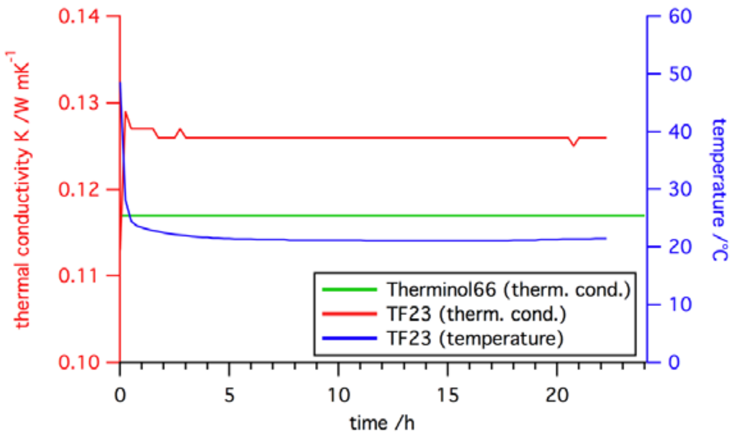


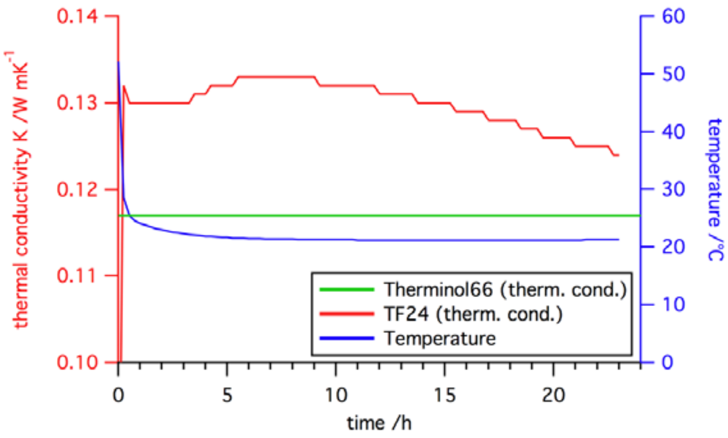


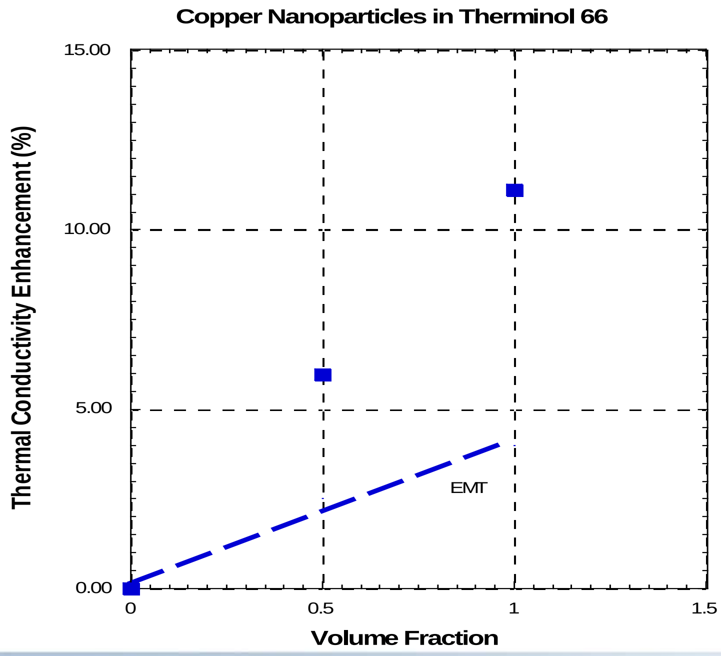
Phase pure copper synthesized and dispersed in Therminol

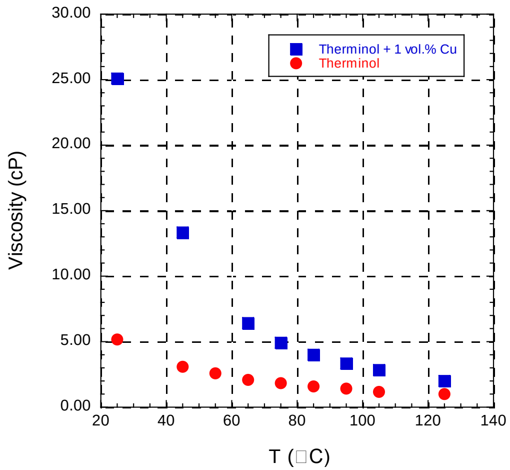
Accomplishments

Thermal Conductivity of Therminol HTF with Cu Nanoparticles







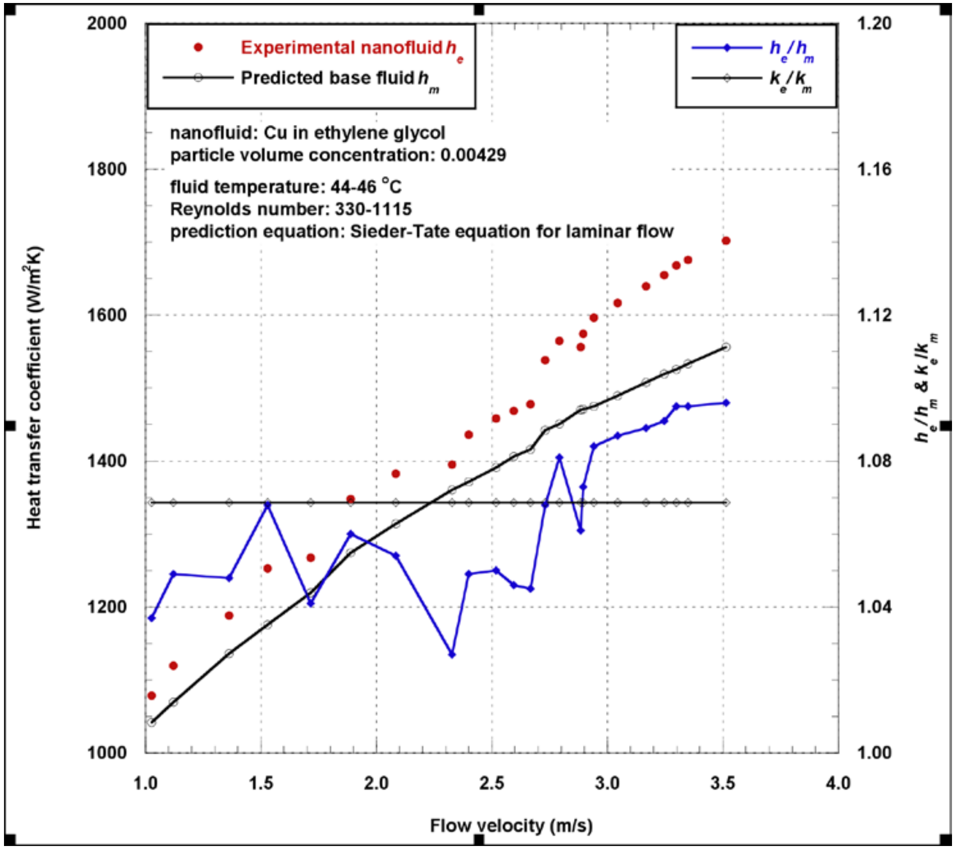


Enhanced Thermal Conductivity
Stable fluid

Long-term stability of the fluids is important

Accomplishments

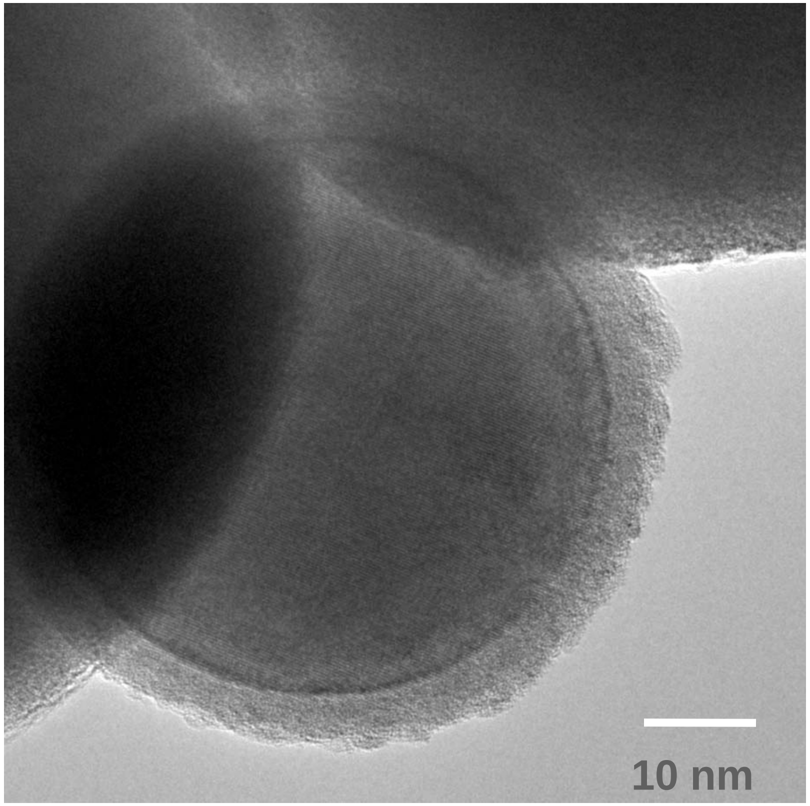
Heat Transfer Measurements of Cu Nanoparticles in Ethylene Glycol

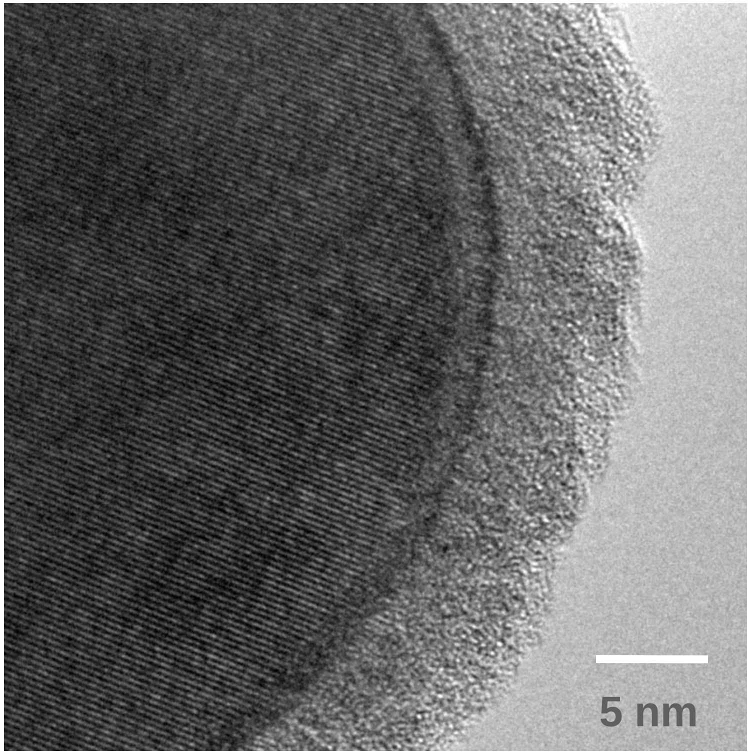


- Heat transfer measured in laminar regime
- Results consistent with thermal conductivity enhancements

Accomplishments

High Resolution TEM of Core/Shell Nanoparticles

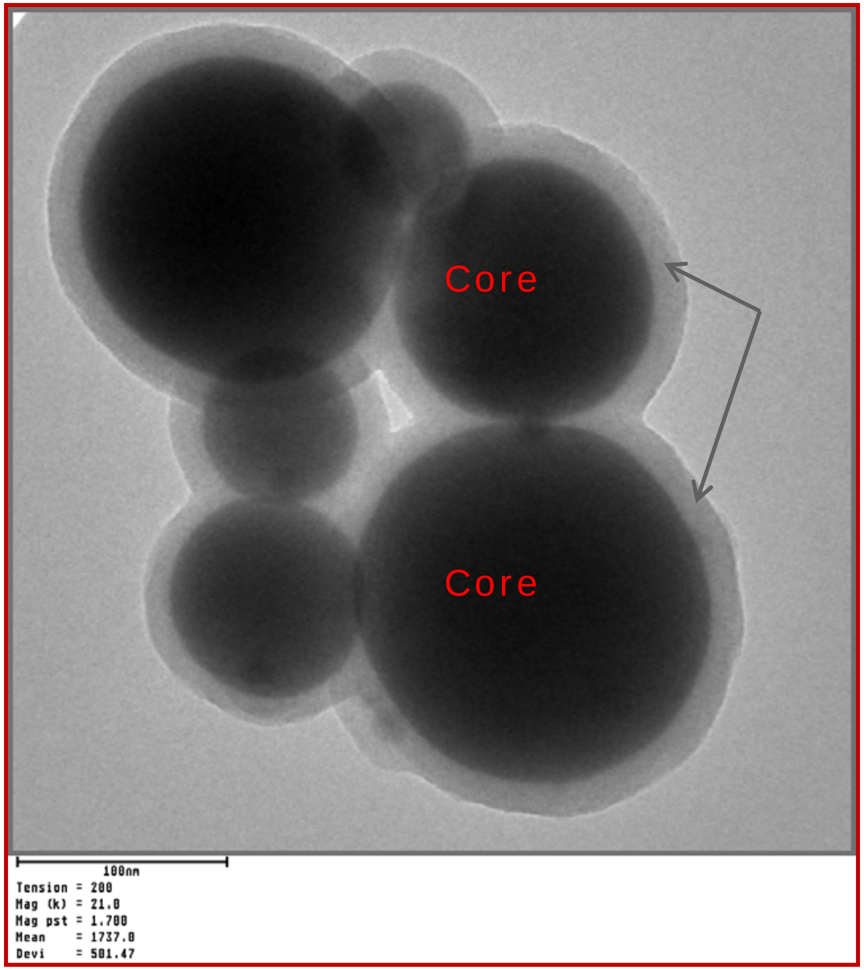




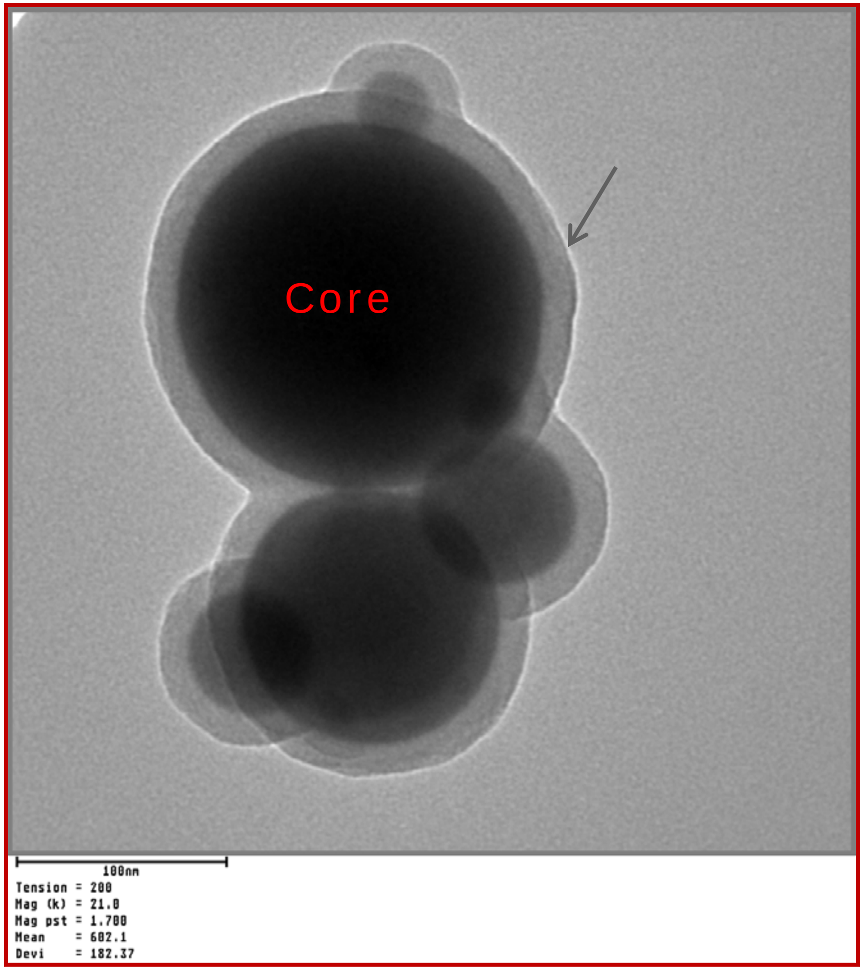
Accomplishments

TEM image of core/shell nanoparticles after several melting/freezing runs

Before



After

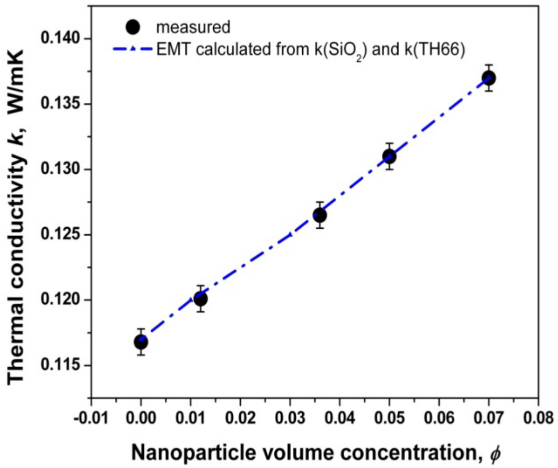


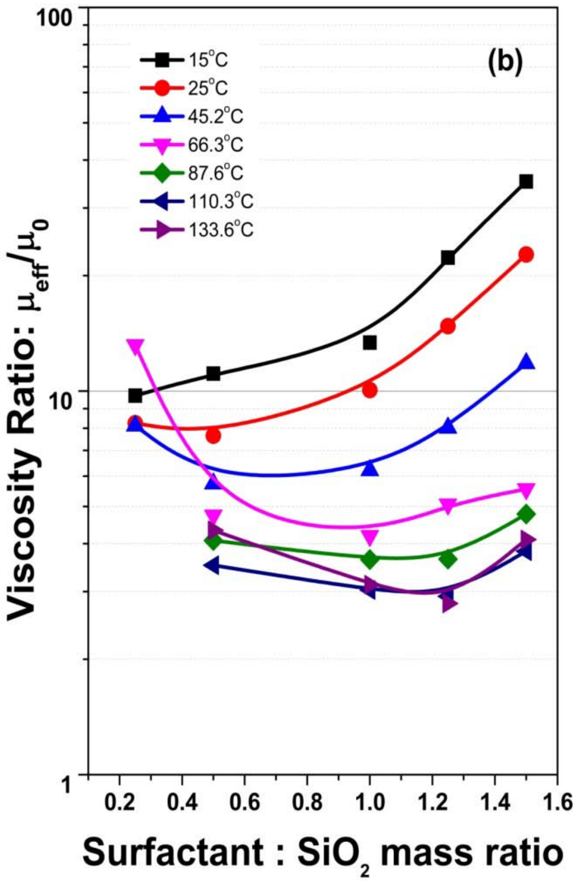
Accomplishments

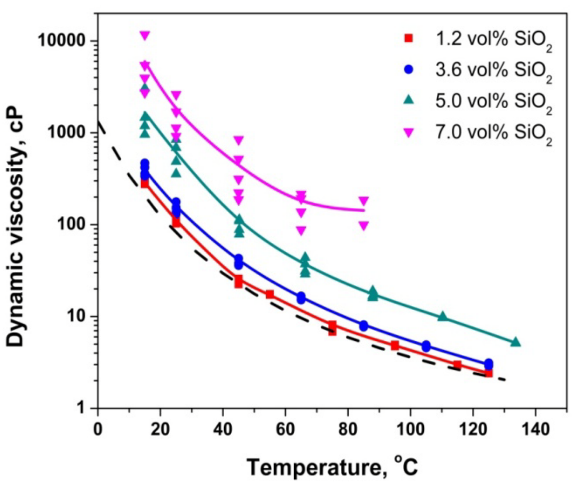
Investigation on silica dispersion nanoparticles In Therminol

Commercial 10-20 nm particles

Dispersed in Therminol using surfactant





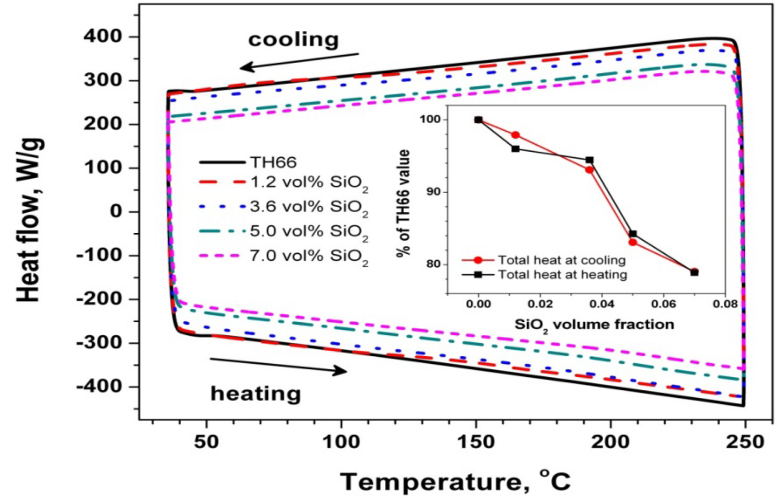


Timofeeva, Moravek, and Singh, manuscript submitted J. Colloid & Interface Sci.

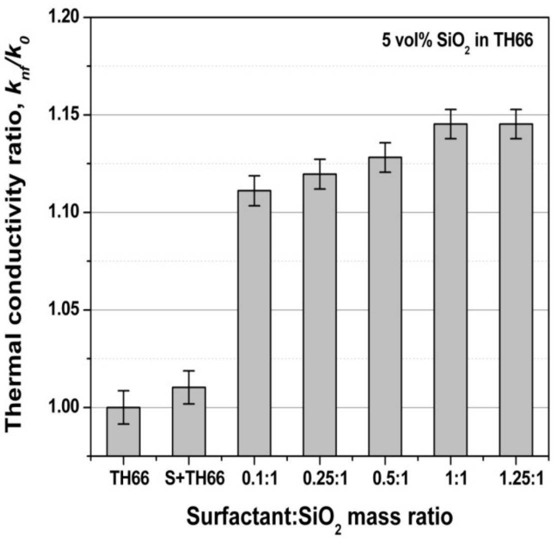
Accomplishments

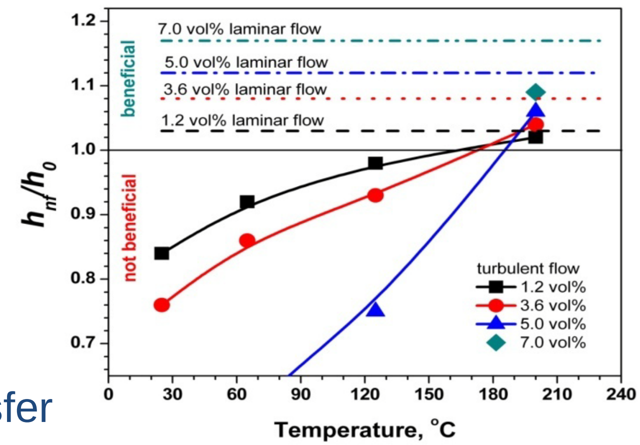
Investigation on silica nanoparticles in HTF

Differential Scanning Calorimetery



Optimization of surfactant content





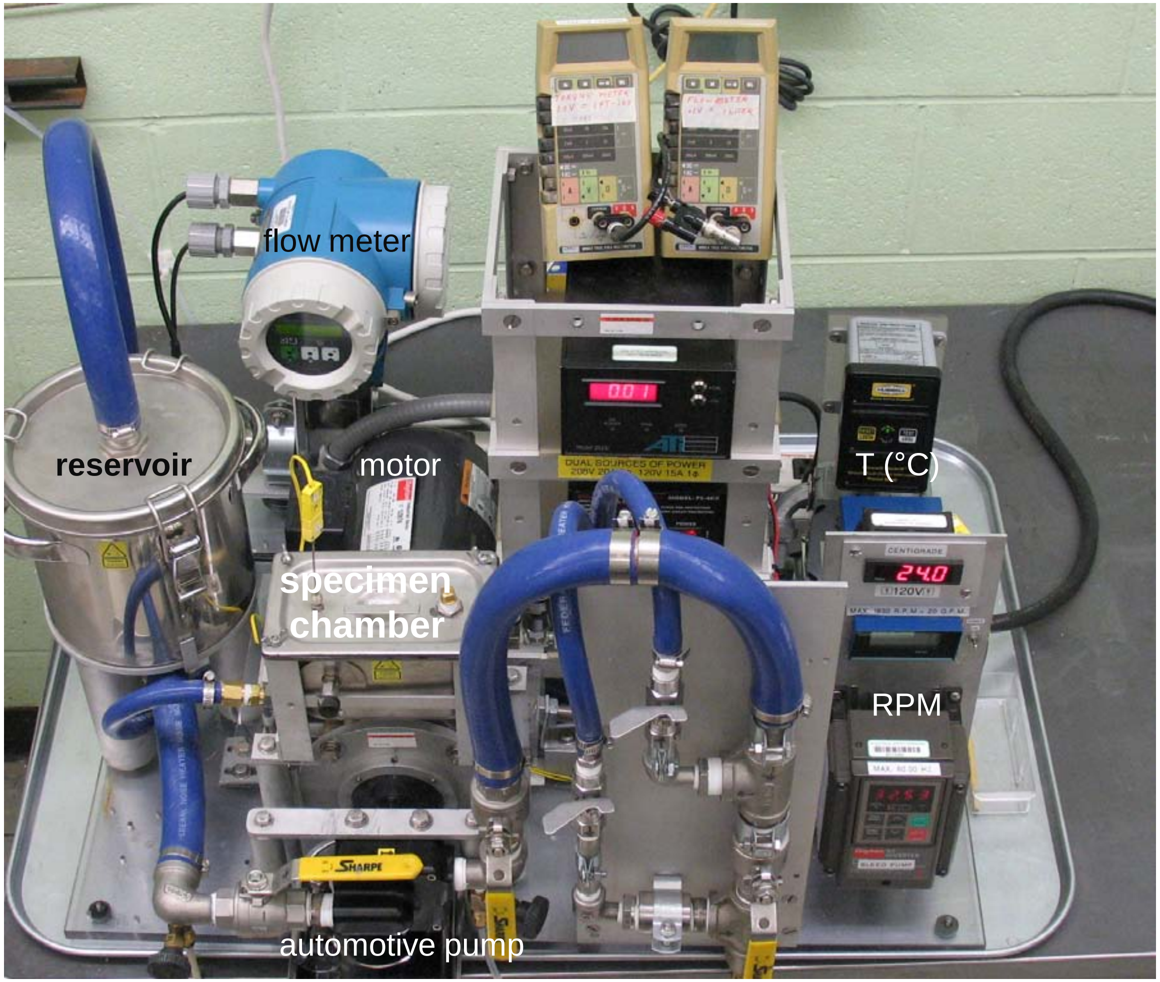
In laminar flow, overall all temperature range

In turbulent flow, T>180°C for enhanced heat transfer

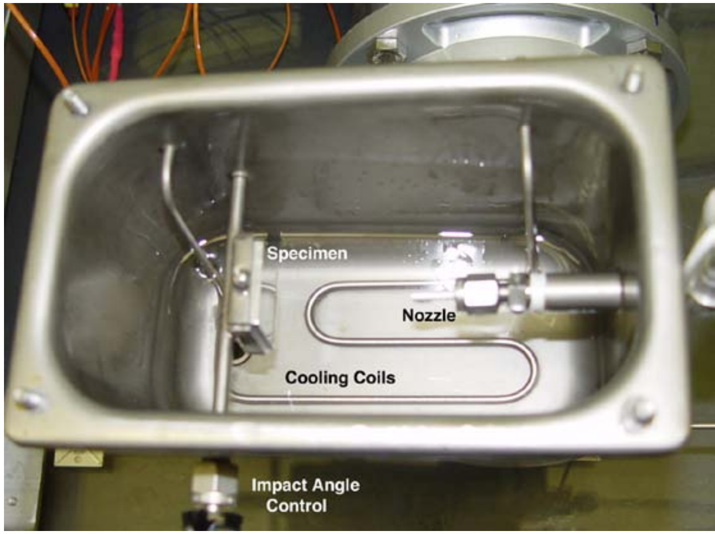
Timofeeva, Moravek, and Singh, manuscript submitted J. Colloid & Interface Sci.

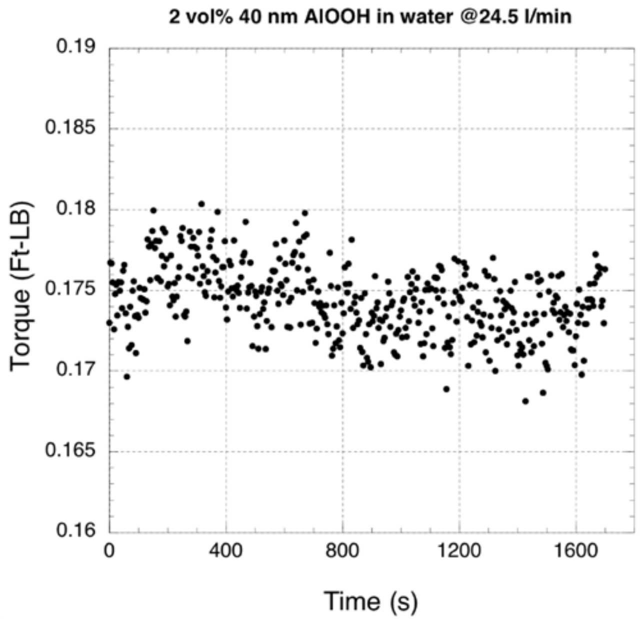
Accomplishments

Pumping Power, Pressure Drops & Erosion



Torque measurement and Data logger hidden behind





Summary

- The goal of the project is to enhance the thermal properties (heat transfer & storage) of HTFs by incorporation of multifunctional nanoparticles.
- Copper nanoparticles synthesized and dispersed in Therminol. Increased thermal conductivity and heat transfer property (in laminar regime) over the base fluid.
- Core/shell nanoparticles synthesized and dispersed in Therminol. Structural evaluation completed. Stability of the core/shell nanoparticles demonstrated.
- Investigation to optimally disperse SiO_2 nanoparticles in Therminol completed.
- Test rig to evaluate mechanical effects of the nano-HTF completed.

Future Work

- Establish stability of the copper/Therminol HTFs for higher particle concentrations and conduct thermal property measurements
- Conduct detailed thermal analysis (heat transfer & calorimetric) on the core/shell nanoparticles dispersed in Therminol
- Establish durability of the nanoparticles and optimize their melting/recrystallization behaviors
- Synthesize metallic/intermetallic core/shell nanoparticles and disperse them in salt based HTFs (Hitec XL)
- Conduct thermo-physical characterizations on the salt based nano-HTFs; investigate performance & durability

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